Bottom Interaction in Long Range Acoustic Propagation

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LONG-TERM GOALS

Analysis of data from the NPAL04 experiments has shown that there are three principal types of arrival in long-range ocean acoustic propagation: 1) arrivals predicted by PE model calculations (RR, RSR, RBR, SRBR ray paths and the mode-like finale region), 2) deep shadow zone arrivals arising from the spread of energy below PE predicted turning points (caustics) and attributed to internal waves (Van Uffelen *et al.*, 2009), and 3) deep seafloor arrivals which can be the largest arrivals observed on seafloor receivers and do not correspond to turning points or any other features in the PE predicted path (Stephen *et al.*, 2009; Stephen *et al.*, 2008). Coda and "bottom junk" have been ubiquitously observed on acoustic receptions on seafloor receivers and are traditionally attributed to incoherent reverberation and scattering. The OBS data on NPAL04 has shown that there are robust, coherent, discrete arrivals that contribute to the coda and bottom junk. The long-term goal of this project is to understand the role of bottom interaction in long-range ocean acoustic propagation. At the moment we do no understand the physical mechanisms responsible for the deep seafloor arrivals and we do not understand the implications for seafloor receptions in shallower water.

OBJECTIVES

On previous NPAL (North Pacific Acoustic Laboratory) tests acoustic arrivals near 75Hz were observed on bottom-mounted hydrophones in the shadow zone well below the SOFAR channel. Dushaw et al (1999) note: "This result is surprising, and no currently available theory accounts for this anomalously deep acoustic energy." There are two prominent hypotheses to explain the energy in the shadow zones: 1) energy is scattered from internal waves and fine structure in the ocean, or 2) long range sound propagation in the ocean involves coupled modes between the ocean sound channel and the sub-seafloor (Butler and Lomnitz, 2002; Park *et al.*, 2001). The latter hypothesis could involve scattering from roughness and lateral heterogeneity at the seafloor or shear wave and interface wave effects in the soft sediments.

There are two specific objectives of this project. 1) Quantitatively compare the signal (near 75 Hz) and noise levels on the hydrophones and geophones at the seafloor to the hydrophones in the sound channel. Deep shadow zone and deep seafloor arrivals are a ubiquitous feature of long range sound propagation in the ocean (Figure 1). 2) By comparing the vertical particle velocity from the geophone to the pressure from the hydrophone we can infer the role of rigidity in the propagation process. For a

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14. ABSTRACT
Analysis of data from the NPAL04 experiments has shown that there are three principal types of arrival in long-range ocean acoustic propagation: 1) arrivals predicted by PE model calculations (RR, RSR, RBR, SRBR ray paths and the mode-like finale region), 2) deep shadow zone arrivals arising from the spread of energy below PE predicted turning points (caustics) and attributed to internal waves (Van Uffelen et al., 2009), and 3) deep seafloor arrivals which can be the largest arrivals observed on seafloor receivers and do not correspond to turning points or any other features in the PE predicted path (Stephen et al., 2009; Stephen et al., 2008). Coda and "bottom junk" have been ubiquitously observed on acoustic receptions on seafloor receivers and are traditionally attributed to incoherent reverberation and scattering. The OBS data on NPAL04 has shown that there are robust, coherent, discrete arrivals that contribute to the coda and bottom junk. The long-term goal of this project is to understand the role of bottom interaction in long-range ocean acoustic propagation. At the moment we do no understand the physical mechanisms responsible for the deep seafloor arrivals and we do not understand the implications for seafloor receptions in shallower water.

15. SUBJECT TERMS

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plane wave in a uniform acoustic medium the ratio of pressure to velocity is simply the acoustic impedance (density times phase velocity) (Jensen *et al.*, 1994). For interface waves at the seafloor that are proposed to be a significant mechanism in the coupled mode problem, however, the relationship between pressure and particle velocity is more complicated and involves phase shifts depending on the type of interface waves (Rauch, 1980; Sutton and Barstow, 1990).

"A more specific science objective is to understand the acoustic energy that arrives near and below the critical depth (where the deep sound speed equals the highest sound speed in the upper ocean). In previous experimental work, both for NPAL and AMODE (*Dushaw et al*., 1999), we observed anomalously high signal to noise ratios at these great depths. Some of the observed effects may be due to decreased levels of ambient noise, but apparently not all. For this work the DVLA and the four ocean bottom seismometers (OBS) that we deployed around the DVLA are important assets. .... " (quoted from page 3 of the LOAPEX Cruise Report (Mercer *et al.*, 2005)).

APPROACH

Ocean bottom seismometer (OBS) instrumentation was "piggy-backed" on the NPAL/LOAPEX controlled source cruise that began in September 2004 (Mercer *et al.*, 2005; Mercer and Howe, 2004). The OBSs were retrieved on the SPICE04 recovery cruise in May 2005 (Worcester, 2005). Direct funding for the OBS's came from WHOI and NSF. ONR provided the additional ship time for the deployments and recoveries and has provided support for the data analysis. (We are particularly grateful to the Chief Scientists, Jim Mercer and Peter Worcester, for helping to make this possible.)

LOAPEX transmissions were made at seven stations at nominal ranges of 50, 250, 500, 1000, 1600, 2300 and 3200km from the DVLA. Water depths at the DVLA was 5045m (the OBS's were deployed about 2km north, south, east, and west from the DVLA in comparable water depths). Water depth along the 3200km path to the furthest transmission station varied between 4800 and 6000m with only three or four locations where the depth was shallower than 5000m (see Figure 1 of Stephen et al (2009)). From CTD casts at the seven stations the critical depth is everywhere shallower than 4600m (see Figure 3 of Stephen et al (2009)). Since the water wavelength at 75Hz is about 20m the seafloor is many wavelengths below the critical depth and sound levels at the seafloor should be quite low based on conventional analysis.

Matt Dzieciuch (SIO) has been particularly helpful with OBS locations and ranges and he has carried out all of the PE modeling. Rex Andrew (APL/UW) has provided invaluable advice and interactions on the signal processing including the code for replica correlations and an analysis of the effects of Doppler processing. John Colosi (NPGS), Peter Worcester (SIO) and Jim Mercer (APL/UW) have provided valuable insights to the analysis. Comparisons with other NPAL related analysis by Lora Van Uffelen (SIO), Ilya Udovydchenkov (WHOI) and Jinshan Xu (MIT) has been useful. Tom Bolmer (WHOI) has provided valuable assistance in computer systems and data base management and data quality control.

WORK COMPLETED

The focus in the past year has been on preparing and publishing a JASA paper (Stephen *et al.*, 2009) and a WHOI Technical Report (Stephen *et al.*, 2008) on the observation of the "deep seafloor arrivals". These papers focused on the M68.2 transmissions at 350m source depth to the South OBS and the DVLA. Many issues were resolved including: a) SRBR paths, b) reconciling my work with that of

other NPAL investigators, c) considering the Doppler effects of moving sources, d) the PE modeling and fine tuning experimental parameters such as ranges and sound speed profiles, and e) displaying the results in a succinct and comprehensible manner. Issues raised by the co-authors and reviewers were resolved (for example we added the bathymetry map around the receiver sites, Figure 2). Preliminary results showing very late seafloor arrivals, arriving many seconds after the finale, were presented at the 2008 Fall ASA, the 2009 NPAL workshop, a CTBTO workshop in Vienna and a visit to ONR Arlington.

RESULTS

Replica correlations have been carried out on all of the available OBS hydrophone and geophone data. The geophone (South OBS, East OBS and West OBS) and DVLA (lower most hydrophone) data for the M68.2 sequences at 350m source depth are shown for individual (30sec) transmissions in Figure 1 for ranges from 250km to 3200km. The deep seafloor arrivals show a consistent pattern on all three OBSs and are weak or not observed on the DVLA. Even though the OBS is on the seafloor about 20 wavelengths below the bottom of the sound channel, clear arrivals can still be detected out to 3200km.

The preliminary results show that vertical geophones on the seafloor (4973m, 4997m and 5035m depth) have more and later ray-like arrivals than a hydrophone in the sound channel (4250m depth, about 750m above the seafloor) (Figure 1). Some of these arrivals correspond either to energy that is predicted by the parabolic equation method or to leakage of energy below shallower turning points (see Figure 4 of Stephen et al (2009)).. Based on travel time, amplitude and waveform, however, many of these “deep seafloor arrivals” do not correspond to any previously recognized oceanic propagation path. It is these unexplained, large amplitude later arrivals that contribute the most to the long range (up to 3200km) deep seafloor receptions.

We are preparing a technical report and research paper on the complete dataset which will outline the constraints placed on possible physical mechanisms. Results will also be reported at the Fall 2009 ASA meeting.

IMPACT/APPLICATIONS

Formerly the acoustic receptions on deep seafloor hydrophone arrays have been interpreted in terms of traditional ocean acoustic paths (refracted-refracted, refracted surface-reflected and surface-reflected bottom reflected) and leakage directly below caustics or turning points (deep shadow zone arrivals) in the ocean sound channel. Our analysis indicates that there is a new, unexplained class of arrivals that appears primarily on deep seafloor receivers. We call these "deep seafloor" arrivals. Deep seafloor arrivals appear to be an interface wave whose amplitude decays upward into the water column. The interface wave could be a shear-related mode coupled to the sound channel propagation (Butler, 2006; Butler and Lomnitz, 2002; Park *et al.*, 2001) or it could be excited by secondary scattering from bottom features (Chapman and Marrett, 2006; Dougherty and Stephen, 1988; Schreiner and Dorman, 1990). Understanding the physical mechanisms responsible for these arrivals will be essential for the proper interpretation of long-range receptions on deep seafloor receivers.

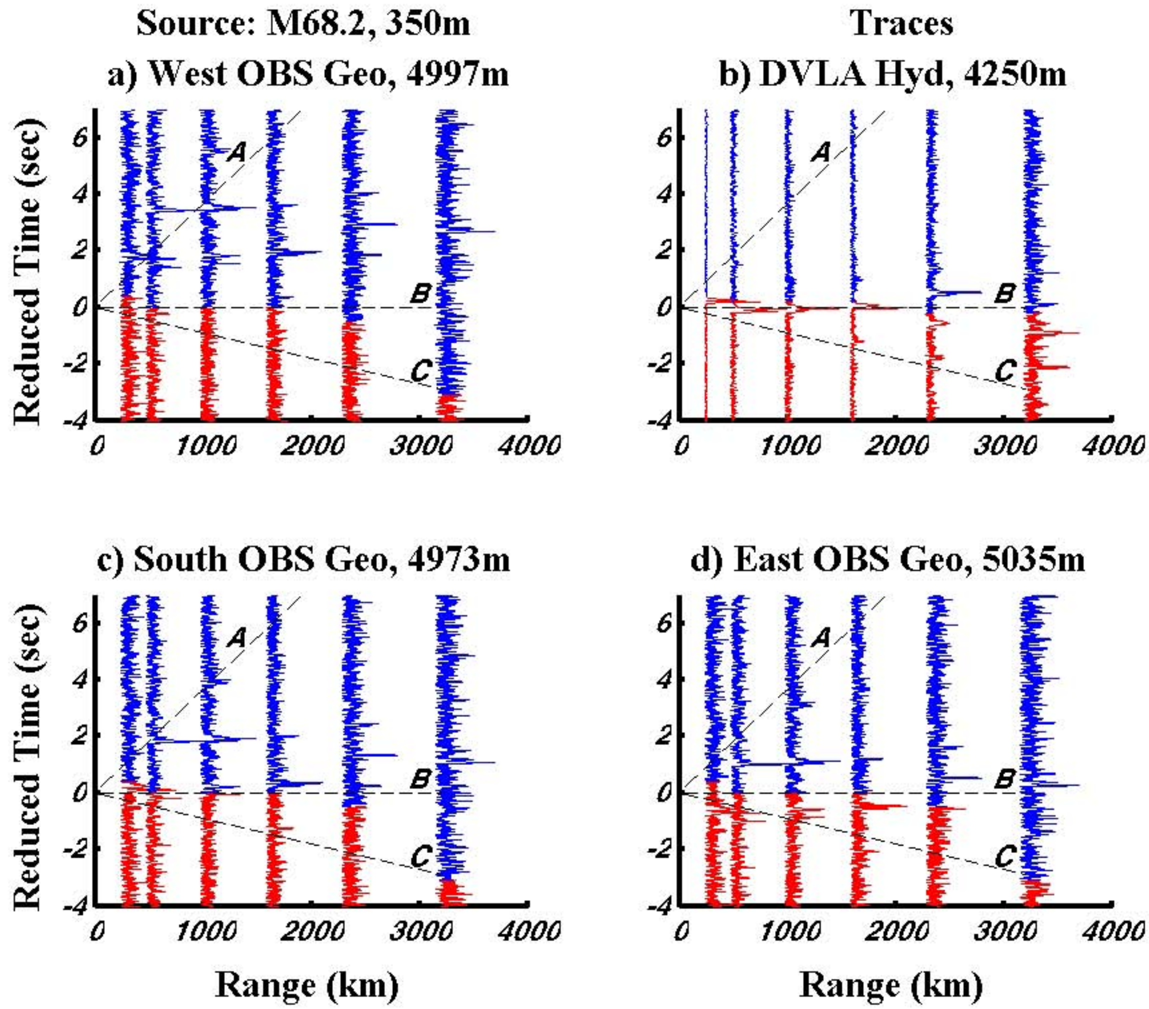

Figure 1: Stephen et al (2009; 2008) focused on stacked traces to just the South OBS and the deepest hydrophone on the DVLA. This figure compares receptions on all four receivers (see Figure 2) for a single 30sec transmission. At each range the same transmission is shown for all four receivers. As described in the 2009 paper, red indicates "PE predicted" arrivals and blue indicates either "deep shadow zone arrivals"(observed on the DVLA as well as the OBSs) or "deep seafloor arrivals" (primarily observed on the OBSs). For example the blue arrivals at 2sec reduced time for ranges from 500 to 1600km are "deep seafloor arrivals". The robustness of these arrivals over all three ocean bottom receivers is remarkable. Dashed lines correspond to three relevant velocities: A- 1.477km/s - the apparent sound speed of the latest arrival at T500, T1000 and T1600, B - 1.485km/s - the apparent sound speed of the largest PE predicted at the deepest hydrophone of the DVLA which seems to separate the known early arrivals from the late unknown arrivals and C - 1.487km/s - the apparent sound speed of the earliest arriving energy at the OBSs and DVLA, which corresponds to the deepest turning rays.

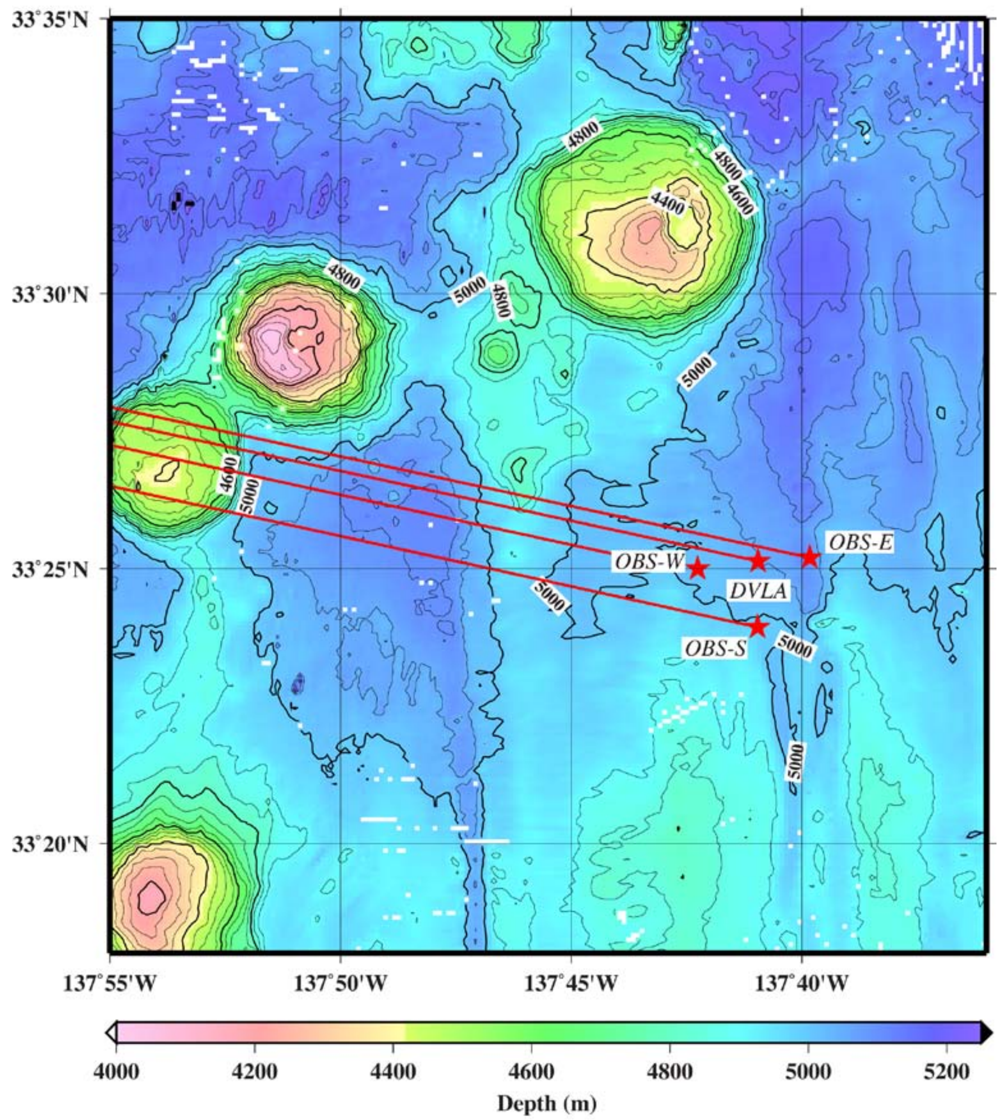

Figure 2: This figure shows the locations of the three OBSs and the DVLA with their geodetic paths to the source locations. The paths are collinear within 3km. The swath map bathymetry (Worcester, 2005) shows that all three paths pass over a seamount on the seafloor that is deeper than 4400m. Could the unexplained arrivals be scattering from this deep seamount or side-scattering from the others, which rise to about 4000m?

TRANSITIONS

Transitions to 32ASW project "Behavior of very low frequency near bottom ambient noise in deep water".

RELATED PROJECTS

LOAPEX - ONR Award Number N00014-1403-1-0181

SPICEX - ONR Award Number N00014-03-1-0182

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PUBLICATIONS

Stephen, R. A., Bolmer, S. T., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Buck, L. J., Mercer, J. A., Colosi, J. A., and Howe, B. M. (2009). "Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation," J. Acoust. Soc. Am. **126,** 599-606.

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PATENTS

None

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